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WEIGHTLESS MAN: SELF-ROTATION TECHNIQUES

Philip V. Kulwicki
Behavioral Sciences Laboratory
6570th Aerospace Medical Research Laboratories

Edward J. Schlei
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Dayton, Ohio

TECHNICAL DOCUMENTARY REPORT NO. AMRL-TDR-62-129

October 1962

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Behavioral Sciences Laboratory
6570th Aerospace Medical Research Laboratories
Aerospace Medical Division
Air Force Systems Command
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Project No. 7184, Task No. 718405

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FOREWORD

This self-rotation study was suggested by Captain John C. Simons, Crew Stations Section, Human Engineering Branch, 6570th Aerospace Medical Research Laboratories. This work fulfills a requirement under Project No. 7184, "Human Performance in Advanced Systems," Task No. 718405, "Design Criteria for Crew Stations in Advanced Systems." Basically, this report is an expansion by Kulwicki of the original work completed by Schlei and Vergamini (ref. 10), University of Dayton Research Institute under Contract AF 33(616)-6256. This study was initiated in November 1961 and was completed in February 1962.

Special acknowledgment is made to the following people in this Headquarters:
Mr. Charles Clauser and the Anthropology Section, Behavioral Sciences Laboratory, for their many helpful suggestions and construction of the model man; and to Mr. Otto Schueller, Protection Branch, Life Support Systems Laboratory, for his technical critique of the program.

ABSTRACT

To be an effective weightless worker, an individual must be able to achieve and maintain a stable attitude with respect to his vehicle. If the worker is to have this capability, he must be able to control both translation and rotation. Translation may not be controlled without hardware, whereas rotation may. The purpose of this study was to investigate the possibility of body rotation by limb manipulation. This self-rotation is analyzed by the application of theoretical mechanics to a rigid mathematical model composed of six cylindrical segments. A quantitative evaluation, based on the mathematical model, is made for one maneuver to determine the expected degree of rotation. As a result of this analysis, a series of selected maneuvers are proposed to give man the capability for rotation about three mutually perpendicular axes. The nine maneuvers are intended to provide an effective rotation, while reducing undesirable coupled rotations. In addition, the stability of rotation of various geometrical shapes is investigated to determine if man can expect a self-rotation maneuver to be stable.

PUBLICATION REVIEW

This technical documentary report has been reviewed and is approved.

Walter F. Grether

WALTER F. GRETHER
Technical Director
Behavioral Sciences Laboratory

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INTRODUCTION

Numerous zero-G flights have shown that a man, being flexible, can achieve various limb rotations through body manipulations without the use of external forces. However, the process is neither efficient, nor is the rotational effect always the reaction desired.

THEORETICAL CONSIDERATIONS

To analyze the motions of a body in a weightless environment, the familiar laws of mechanics are applied

$$F = ma$$

where F = force
m = mass
a = acceleration

and,

$$T = I\alpha$$

where T = torque
I = moment of inertia
α = angular acceleration

In the absence of external forces and moments, another useful relationship is the law of conservation of momentum, which states that the total linear momentum and the total angular momentum of a body remain constant. For example, a man may attempt to jump ashore from a rowboat. If the boat is not moored, the man may land in the water, since his momentum toward the shore is balanced by the momentum of the boat away from the shore. Thus, the total momentum of the boat-man system remains zero (fig. 1).

Another example is that of a figure skater rotating with an initial angular velocity and a definite angular momentum. If he extends his arms, his moment of inertia is great and his angular velocity is small. If he draws his arms in, his moment of inertia decreases, but his angular velocity increases so that the total angular momentum remains constant (fig. 2).

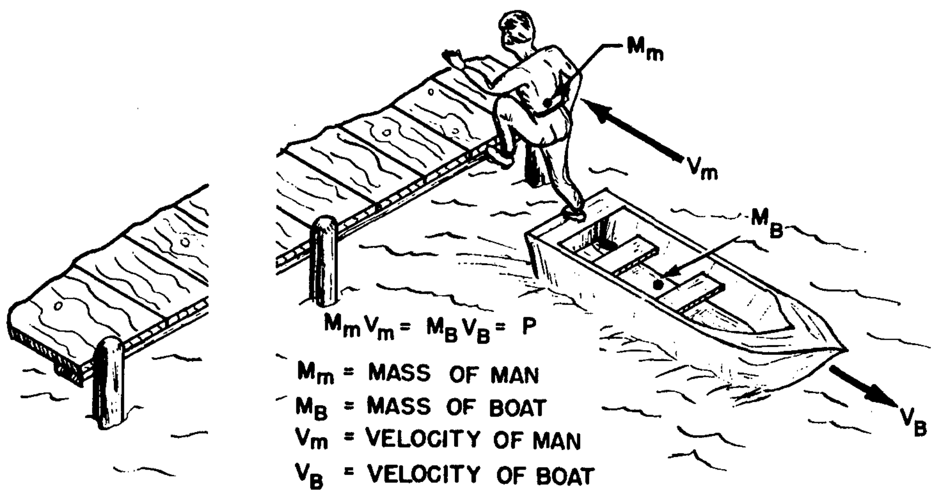


Figure 1. Effects of Linear Momentum

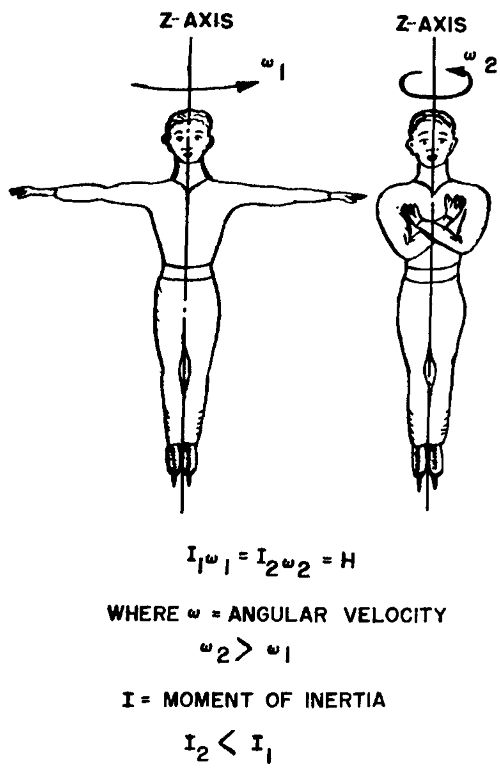


Figure 2. Effects of Angular Momentum

The next step in a mechanics problem is the judicious selection of the free-body, or system. In analyzing a weightless man, the entire man could be considered the system or various parts of the man could be selected as the free-body, depending upon which part of the total solution is being considered. To be more specific, consider the weightless man at rest and free of all external forces and moments. If his entire body is chosen as the system, its center of mass can experience no net rotation since there are no external torques. The linear and angular moments of the system are zero.

The body is flexible, however, and is capable of generating internal forces and moments, such as rotation of one or more limbs, thus imparting angular momentum. However, the rest of the body would rotate in the opposite sense and the resultant angular momentum would remain zero. When the rotation of the limbs stops, the rotation of the remaining parts of the body also stops, and the body attitude will have changed relative to other fixed objects (see fig. 3), however, that is the only change that could occur. His center of mass would have experienced no absolute motion in space throughout his maneuvering, but the man would have sensed motion due to the relative change of attitude with respect to some visual or vestibular reference.

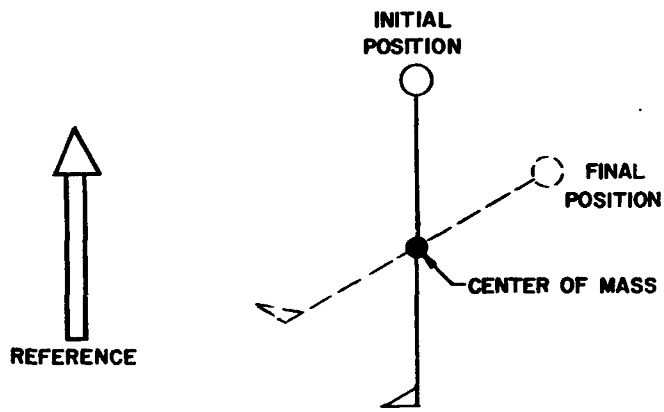


Figure 3. Attitude Change

The same conclusions can be reached if only a segment of the man's body, such as an arm, is assumed to be the system. The forces and moments applied to the arms at the shoulder joint would be considered external loads. Application of the classical laws of mechanics would give the resultant motion of the arms and applying equal and opposite external loads to the remainder of the body (equal actions and reactions) give the resultant motion of that system. Thus, the problem can be analyzed by a number of different applications of the same method. The procedure can become complex if the body is considered as a large number of separate systems.

The action-reaction effects can be considered as the astronaut attempts to twist his upper body about the Z-axis (axis through head and feet). To accomplish this motion he must supply an internal torque at his waist. Considering a torque causing a clockwise rotation as being positive, an angle measured in a clockwise direction can also be considered positive. The application of a positive torque to the upper body must be accompanied by the application of an equal negative torque to the lower body. (The sum of these torques must be zero or rotation will occur.)

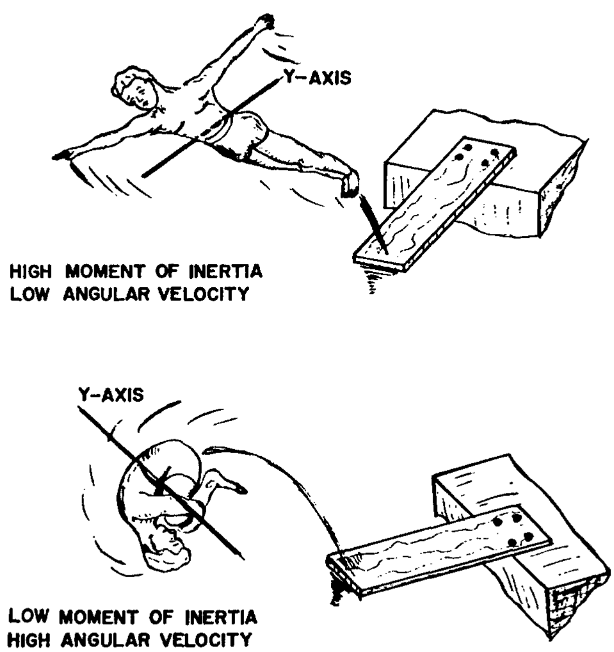
It can be shown that

$$\frac{\theta_u}{\theta_l} = -\frac{I_l}{I_u}$$

where
θ = angular displacement
I = moment of inertia
u = upper body
l = lower body

(see Appendix I, equation 1)

Thus, if the astronaut attempted to twist his upper body through some angle θ_u, his lower body would be twisted in an opposite sense by an amount directly porportional to the ratio of the moment of inertia of the upper body to the moment of inertia of the lower body. If he untwisted in the same manner, he would return to his original position. If, however, he were to change the moment of inertia of either the upper portion or the lower portion or both of them, relatively, one to the other, while still in the twisted state, or while untwisting, for example, by lifting his arms sideways, he would achieve a new attitude. This may be illustrated with an example from the sport of diving (fig. 4). If a diver intends to perform a swan dive, he falls in such a position that his limbs are extended to give him the greatest moment of inertia and the least angular velocity. The diver who wishes to perform a somersault, leaps with his limbs extended, but then rapidly draws them in and lifts his knees to his chest in the tuck position. This gives him a smaller moment of inertia and a greater rate of rotation. The same principle is used by the ballet dancer or figure skater who intends to perform a pirouette. He will first start to rotate with arms extended, but will gradually draw them as close as possible to the axis of rotation, thus increasing the angular velocity by decreasing the moment of inertia. If the moment of inertia will affect the angular velocity, it will also affect the angular displacement. A mathematical discussion of these results is presented in appendix I from which an expression for the net angle of rotation is developed (equation 6).



$$\frac{I_1}{I_2} = \frac{\omega_2}{\omega_1}$$

Figure 4. Effects of Moment of Inertia on Rotation Rates

The reason for the change of moment of inertia for various positions exists within the parallel axis transfer theorem. This theorem states that the moment of inertia about any axis is equal to the sum of the moment of inertia about the centroidal axis plus the product of the mass of the body times the square of the perpendicular distance between axes.

$$I_t = I_c + mD^2$$

where I_t = total moment of inertia
I_c = centroidal moment of inertia
m = mass of body
D = perpendicular distance between the axes

The fact that the distance is squared is the greatest influence on the total moment of inertia. This may be illustrated further by the definition of moment of inertia.

If a body could be divided so that the masses are arbitrarily small, the sum of the masses would equal the total mass of the body. These masses are called differential masses. If we multiply each differential mass times the square of its respective radius from the axis of rotation, and add up all these products, the result represents the moment of inertia of the body about its centroidal axis of rotation. In equation form

$$I_c = \int r^2 \, dm$$

where dm = differential mass
r = radius to the differential mass

Since both the definition of the moment of inertia and the parallel axis transfer theorem contain a term of the radius squared, we may say that moment of inertia reflects the importance of the distribution of mass. Since the moment of inertia changes with the square of the distance, the minimum moment of inertia is found where the components of a body are located as near the centroidal axis as possible, while the maximum moment of inertia is found where the components of a body are located as far from the centroidal axis as possible.

This technique for changing the moments of inertia of the various portions of the body to effect a change of attitude can be applied quantitatively and qualitatively to numerous and varied situations. Qualitative descriptions of some basic body maneuvers are given in the next section.

SELECTED BODY MANEUVERS

In this section, various possible rotations about the X-, Y-, and Z-axes of the body (fig. 5) are explained and comments made concerning the applicability, advantages, and disadvantages of the motion during weightlessness.

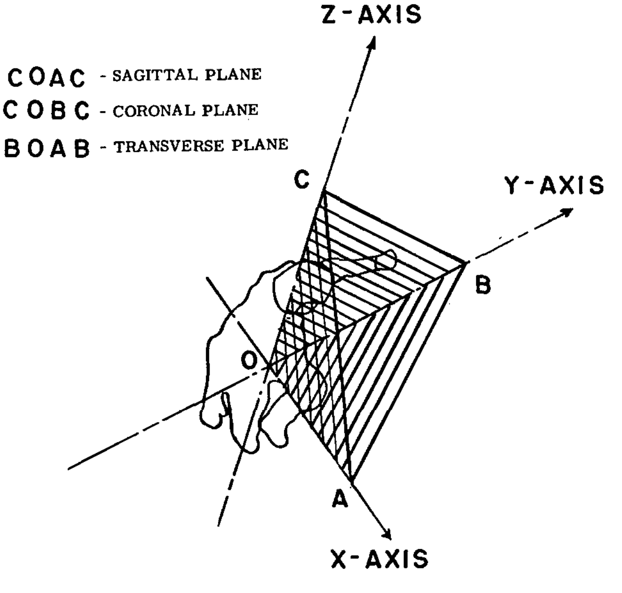


Figure 5. Axis Definition

MANEUVERS ABOUT THE Z-AXIS

Z.1, Cat Reflex* (see fig. 6)

With the body straight and arms down, spread the legs to the sides, then twist the entire torso at the waist about the Z-axis to the right or the left. Holding this twist, extend the arms straight out to the sides, draw the legs together and then untwist by rotating the torso back to its original position. When the arms are lowered to the sides, the subject should have the exact configuration of the limbs with respect to the torso that he began with, but the body as a whole will have rotated a finite amount.

In general, this maneuver may be considered to consist of a four-part cycle. The components of this cycle are given as follows:

1. In the initial stage, the subject has his body straight, arms down, and legs spread to the side in the coronal plane.

2. The subject twists his torso about the Z-axis, the axis of intended rotation. This twist is generated by an internal torque at the waist.

3. The subject increases the moment of inertia of the top of his body by spreading his arms and decreases the moment of inertia of the lower part of his body by drawing in his legs. This change in moment of inertia when coupled to the untwisting causes the lower part of the body to rotate more than the upper part. This change is responsible for the angular displacement.

4. The subject untwists until he faces to the front again, then lowers his arms and returns to the initial stage. When he has achieved the initial stage, the subject is in position to repeat the cycle, and in this way, a rotation about the Z-axis of any amount can be accomplished in steps.

This rotation should be quite symmetrical and free from coupling rotations about other axes. However, if massive items were strapped to the astronaut's back, motions other than the desired rotation might be enhanced.

Z.2, Bend and Twist (see fig. 7)

This maneuver, unlike the cat reflex (Z.1), involves only the movement of the upper part of the body. The subject should try to keep his legs fixed parallel to the Z-axis throughout the maneuver; this position of the legs will tend to minimize induced rotations other than about the desired axis. The maneuver is an approximation to a continuous rotary motion in that some modification is necessary due to the fact that the arms cannot make a full revolution about the Z-axis in the transverse plane. The motion is further modified to reduce a possible coupled rotation about the X-axis. With these ideas in mind, the bend and twist maneuver can be performed in six stages as follows:

1. In the initial stage, the body is straight and the arms are down as in a position of attention.

2. The upper part of the body is bent to the side in the coronal plane.

3. The arms are extended overhead to increase the moment of inertia about the Z-axis of the upper body.

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*Capt Simons assigned the descriptive names to these maneuvers so they can be referred to and understood quickly by space personnel. Training in these maneuvers may be a vital portion of an astronaut's program.

Figure 6. Positions of "Cat Reflex" Maneuver (Z. 1)

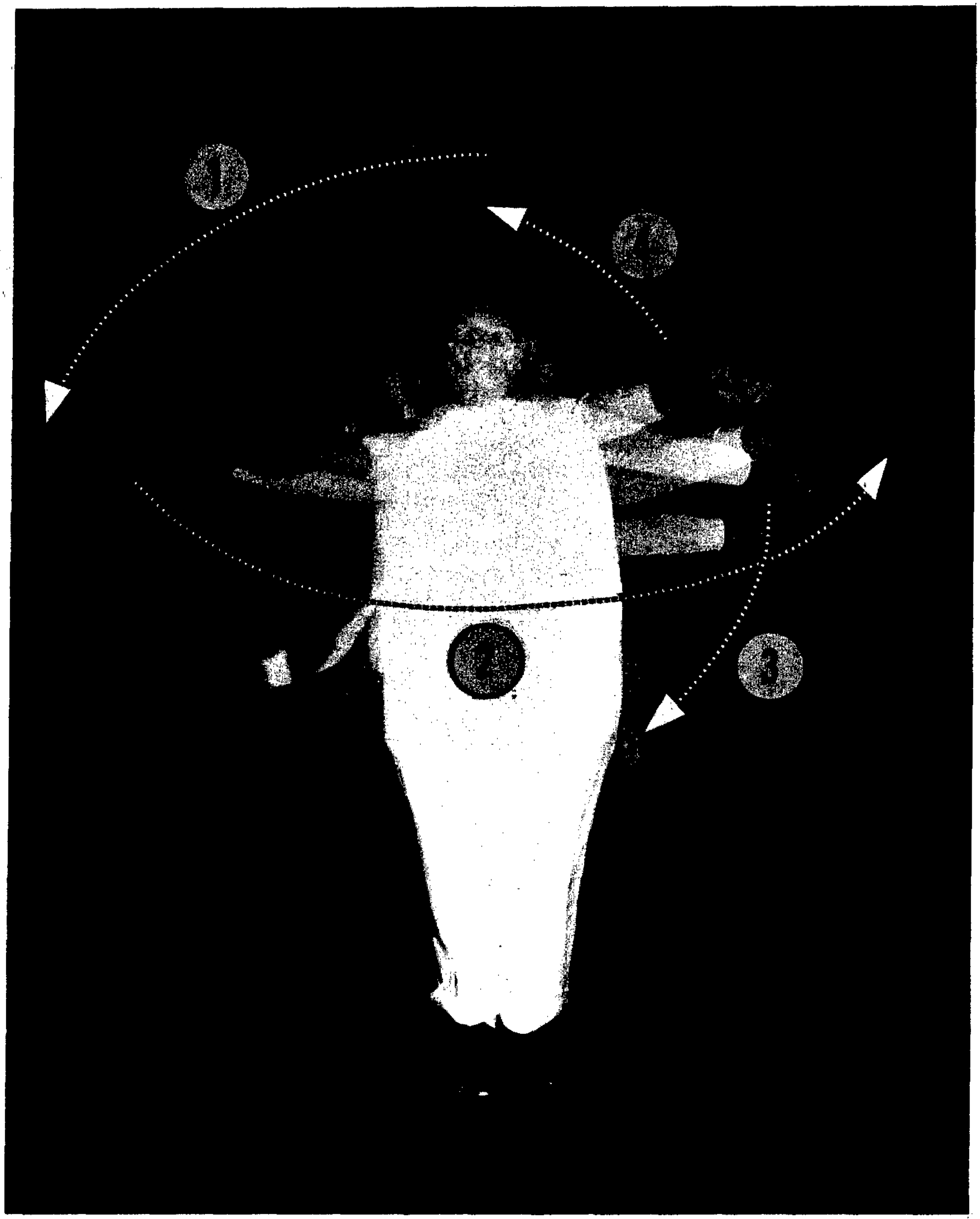


Figure 7. Positions of "Bend and Twist" Maneuver (Z. 2)

4. The entire upper part of the body is then rotated in the transverse plane to the other side. That is, the arms move from the side to the front to the other side, and the back remains nearly horizontal.

5. The arms are drawn in to a down position parallel to the torso. This reduces the moment of inertia, and hence reduces any induced rotation about the X-axis.

6. The torso is returned to the initial stage.

Because of the large moment of inertia of the upper part when it is bent to one side with the arms extended, considerable rotation of the lower part of the body is expected. However, the first step of bending in the coronal plane will cause a rotation about the X-axis, which will be partly compensated for by the unbending at the end of the exercise. The total result is made even more difficult to visualize by the asymmetry of the motion. Additional study of this maneuver is needed before a proper evaluation can be made.

Z.3, Lasso (see fig. 8)

This maneuver is classified as continuous rotary motion since the only movement involved is a continual rotation of the arms. With the body straight and both arms overhead, rotate them continuously in conical motions while keeping the symmetry axes of the cones as near as possible to the Z-axis of the body. Although the moment of inertia of the arms is small compared with that of the rest of the body, this is an easy rotation to perform and, with persistance, an absolute rotation of the entire body can be achieved. This maneuver may be performed with either one or both arms. If only one arm is used, the rotation may be easier to perform, since the axis of the arm's rotation will tend to coincide with the Z-axis; however, the total displacement resulting from each arm rotation will only be half as great.

The greatest disadvantage of this maneuver appears to be the asymmetry of the motion, since the connection of the arm to the body is removed somewhat from the Z-axis. An evaluation of the seriousness of coupling rotations due to this asymmetry will be required.

Z.4, Pinwheel (see fig. 9)

This maneuver is another involving continuous rotary motion, but this time an internal torque at the waist must be continually generated as long as rotation is desired. With the body straight and with the hands on the hips, the upper part of the body is rotated continuously in a conical motion. Actually the motions of both upper and lower parts will describe cones with a common apex at the waist. This maneuver should be more efficient that that described under Z.3, Lasso, in producing rotation, but it is also more difficult to perform. To be symmetrical, the axes of the cones must lie along a straight line. Therefore, the asymmetry of this maneuver may also be a problem, because the astronaut would have to bend as far backwards as he does to the side or to the front.

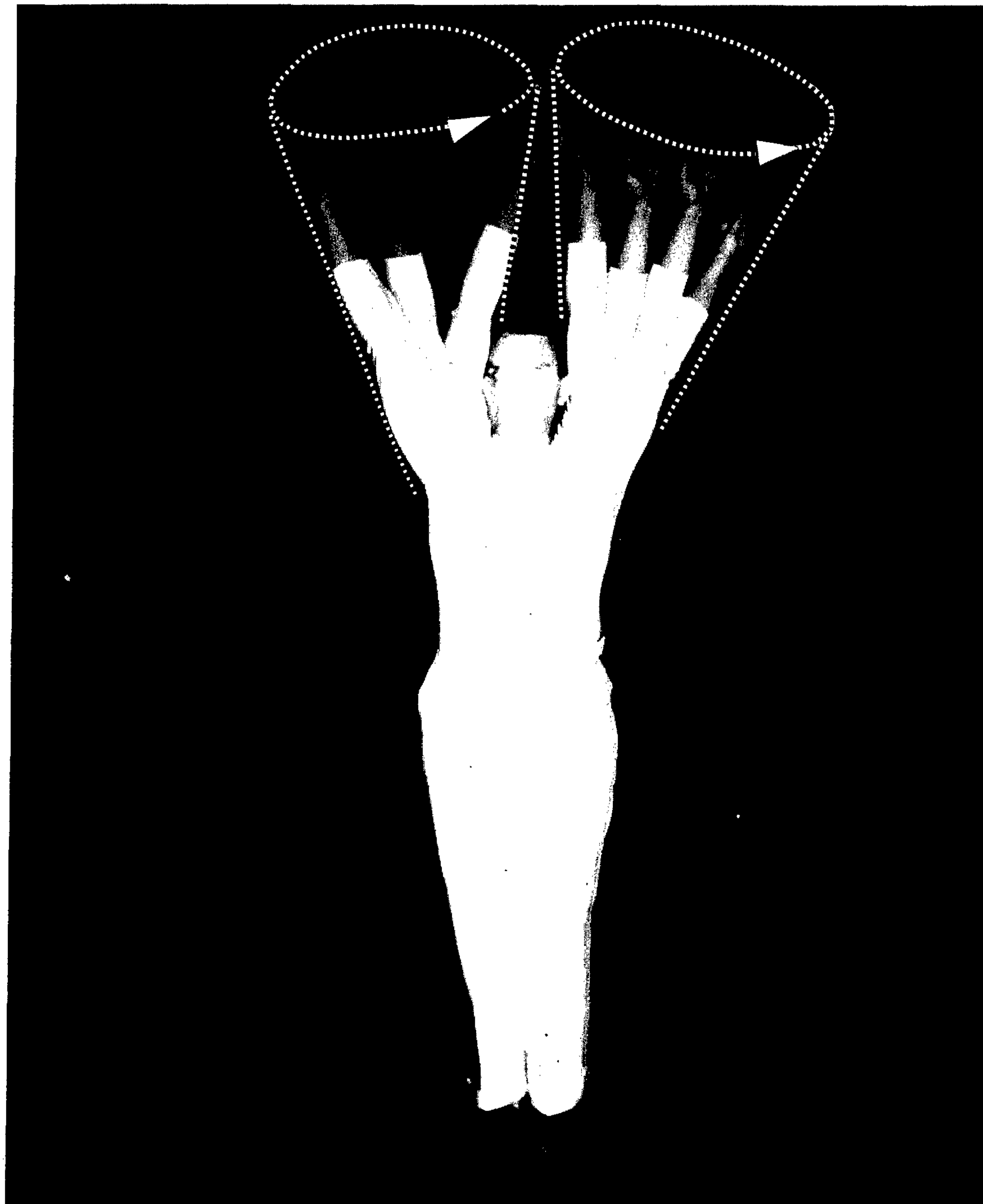


Figure 8. Positions of "Lasso" Maneuver (Z.3)

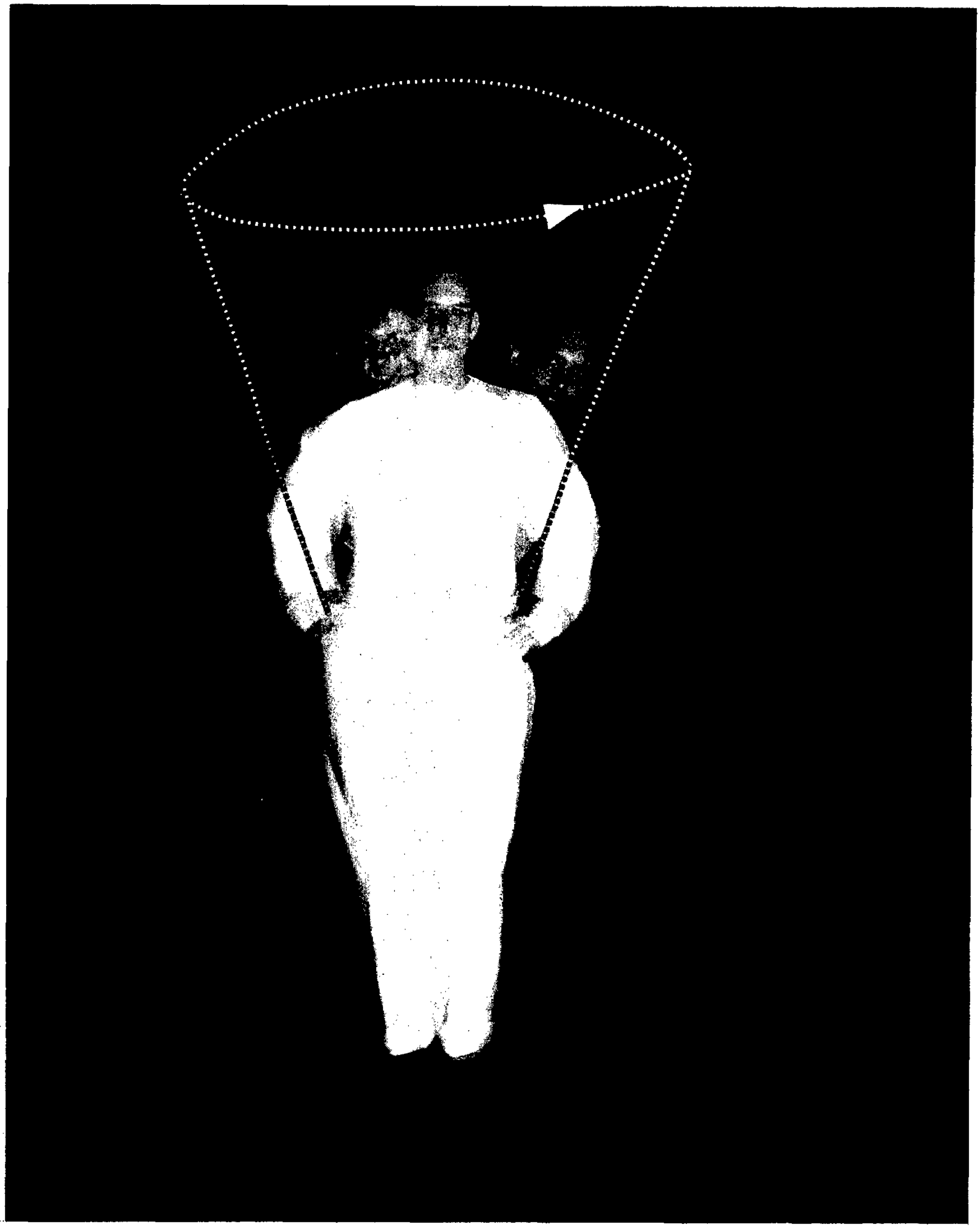


Figure 9. Positions of "Pinwheel" Maneuver (Z.4)

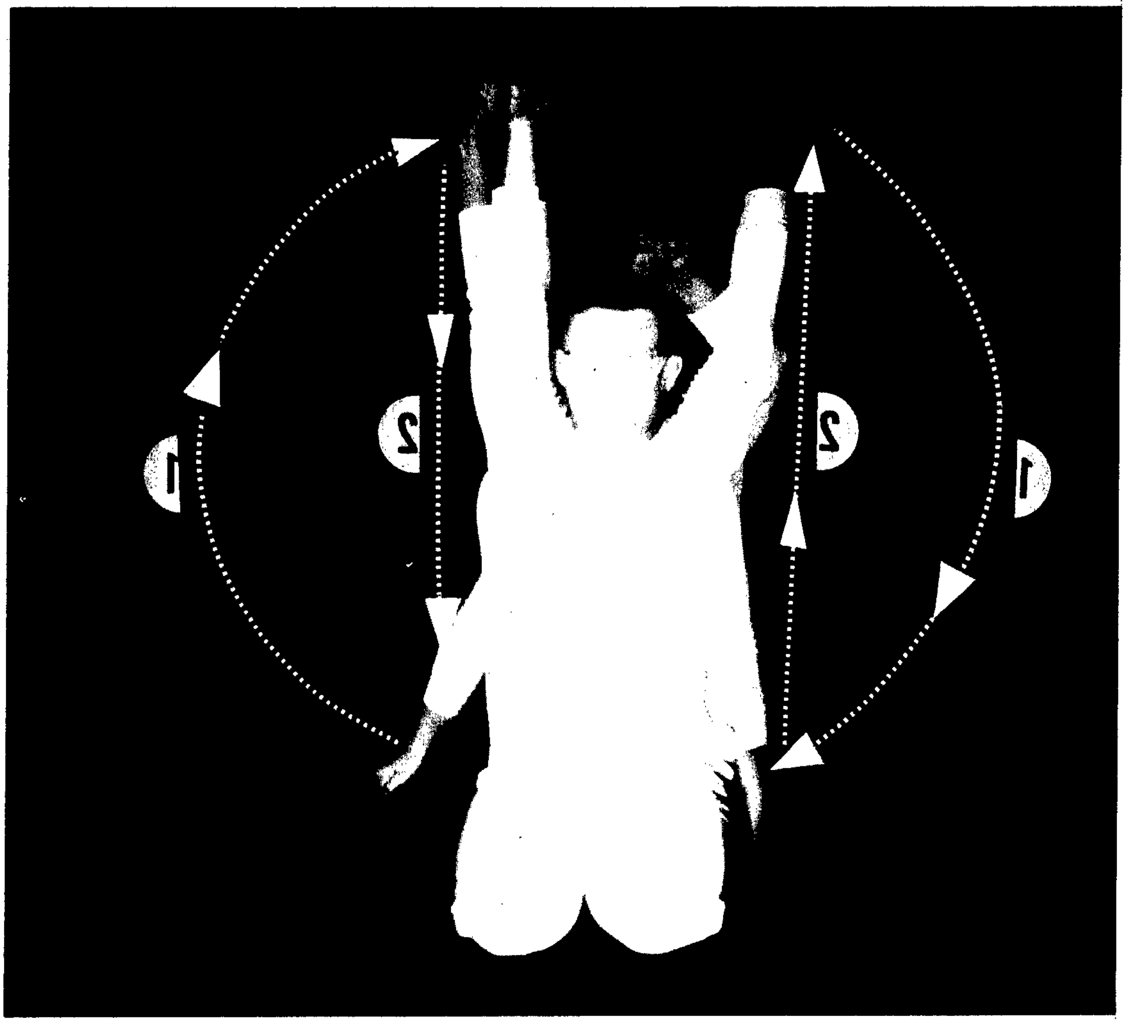


Figure 10. Positions of "Signal Flag" Maneuver (X. 1)

MANEUVERS ABOUT THE X-AXIS

X.1, Signal Flag (see fig. 10)

This maneuver, like Z. 2, Bend and Twist, is an approximation to continuous rotary motion and is modified due to limb restrictions. Again, the maneuver may be described in six stages as follows:

1. With the body straight and the arms at the sides, draw in the legs in tuck position.

2. Next, raise one arm overhead.

3. Rotate the raised arm outward to the side in the coronal plane and down to its original position.

4. At the same time rotate the other arm outward to the side in the coronal plane until it is overhead.

5. Return the arms to their respective positions of step 2 by bending the elbows and moving the hands along the torso while keeping the hands and arms as close to the body as possible. This cycle of arm rotation can be repeated as often as desired so that any amount of rotation may be accomplished.

6. When the desired rotation is reached, extend the legs and return to the initial position.

Although this maneuver requires many arm rotations per body rotation, the motions involved are well within limb extension capabilities. Therefore, the execution of this maneuver should be easily performed.

X.2, Reach and Turn (see fig. 11)

This maneuver is similar to Z.2, Bend and Twist, in that it involves mainly movements of the upper part of the body. Again the legs remain fixed, however, this time they should stay in tuck position, in order that the moment of inertia of the portion above the waist be much greater than the portion below the waist.

The order of steps in the execution of the reach and turn maneuver should proceed as follows:

1. In the initial stage, the body is straight and the arms are down as in a position of attention.

2. The upper part of the body is bent to the side in the coronal plane.

3. The arms are extended overhead to increase the moment of inertia about the X-axis of the upper part of the body.

4. The legs are drawn up in tuck position.

5. The entire upper part of the body is then rotated in the coronal plane to the other side. That is, the arms move from the side to a position directly overhead, to the other side; and the back remains nearly vertical.

6. To return to the initial stage, pull the arms down alongside the torso and extend the legs before bending back to the position of attention.

It is extremely important in this maneuver that the sequence of movements as stated above is maintained. Particularly, the legs must be tucked after the initial bend to the side, and extended before the final bend to the initial position. Secondarily, the arms must be extended after the initial bend to the side, and drawn in before the final bend to the initial position. These two statements indicate that the initial bend to one side must be accompanied by a high inertia of the lower body and a low inertia of the upper body. Similarly, the bend to the other side must be accompanied by a low inertia of the lower body and high inertia of the upper body. It is this change of inertia between bendings that causes a net rotation.

Because of the large moment of inertia of the upper part with the arms extended, considerable rotation of the lower part of the body about the X-axis is expected.

In addition, this maneuver should be quite symmetrical and free from undesirable induced rotations.

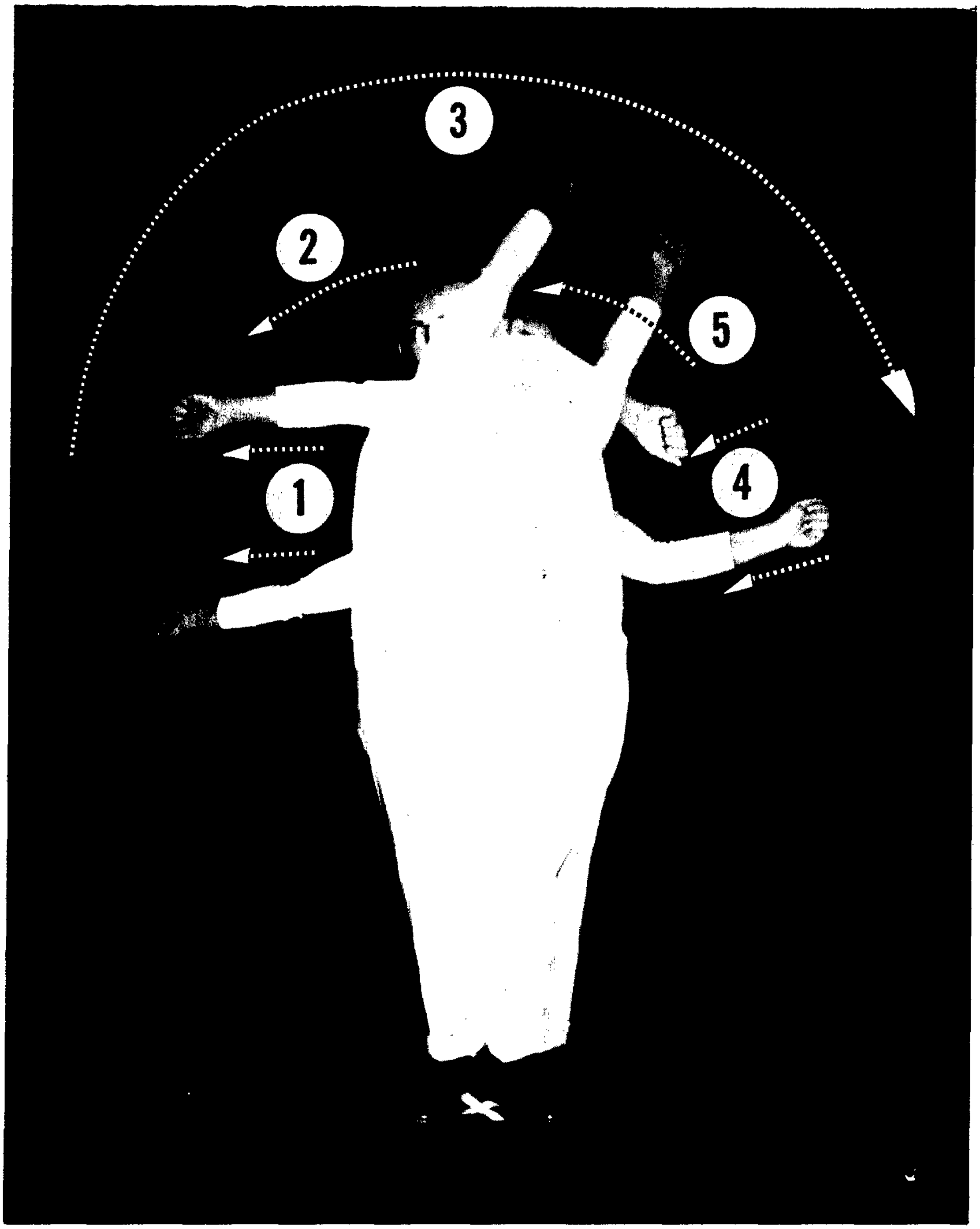


Figure 11. Positions of "Reach and Turn" Maneuver (X. 2)

X. 3, Bend and Twist (see fig. 7)

This maneuver as described in Z. 2 could possibly cause a rotation about the X-axis. With a few adjustments in procedure, this rotation could be increased somewhat, and a combination of rotations about X and Z could result. The procedure should be as follows:

1. Initially, the body is straight and the arms are alongside the torso.

2. The arms are raised so that they are parallel to the Z-axis. Simultaneously, the legs are tucked.

3. The upper part of the body is bent to the side in the coronal plane.

4. The legs are extended and the arms remain extended.

5. The entire upper part of the body is then rotated in the transverse plane to the other side. That is, the arms move from the side to the front to the other side, and the back remains nearly horizontal.

6. The legs are again drawn up in tuck position and the arms remain extended.

7. The entire upper part of the body is then rotated in the coronal plane back to the position of step 3 and the cycle may then be repeated.

Once again, the steps must be performed in the above order if any appreciable X-axis rotation is to accompany the Z-axis rotation. Additional study of this maneuver is necessary to determine if it is a desirable way to achieve a combination of rotations.

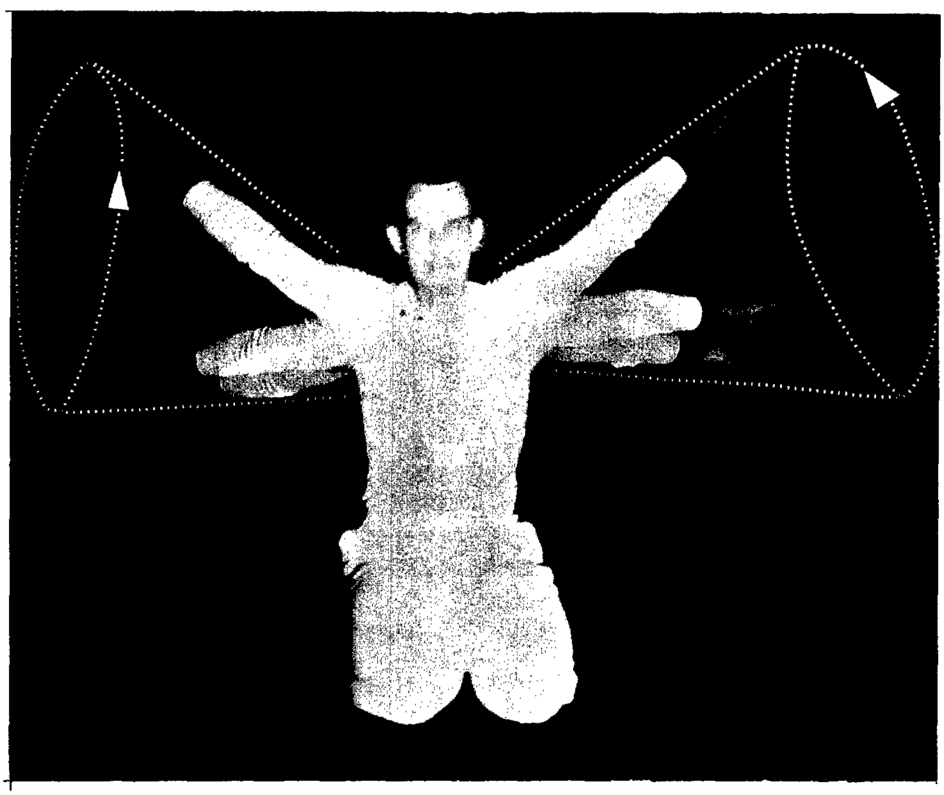


Figure 12. Positions of "Double Pinwheel" Maneuver (Y. 1)

MANEUVERS ABOUT THE Y-AXIS

Y. 1, Double Pinwheel (see fig. 12)

This continuous rotary maneuver has been demonstrated with success in zero-G flights. The procedure is quite simple. With the legs and feet tucked and the arms extended straight out parallel to the Y-axis, rotate the arms simultaneously in conical motions. Although much arm motion is needed to produce body rotation, the technique is easily performed and quite symmetrical.

Y. 2, Touch the Toes (see figs. 13a, 13b)

This maneuver is another containing a four-part cycle. The execution of this maneuver may prove to be difficult due to the asymmetry of the limb manipulations themselves and to a high rate of energy consumption, because some of the limbs and the torso are stressed to the limits of their joint ranges. The sequence of movements may be performed as follows:

1. In the initial state, the body is straight, the arms remain along the torso, and the legs are tucked.

2. The movement about the intended axis of rotation involves first the straightening of the legs to a "locked position" and then a forward bend at the waist of the torso, as in the "touch-the-toes" exercise. Note that initially the arms remain along the torso and after the bending of the torso, the arms should be extended and lie parallel to the legs.

3. The change of inertia and counter-rotation involves first the return of the legs to tuck position and then a backward bend at the waist of the torso until an upright position is reached as in the initial state. Note that the arms are overhead throughout this return to the initial state. When the backward bend is completed, the arms may be lowered; thus the subject is in position for another cycle. Note that maximum rotation will result if all limb and torso manipulations are performed in a sagittal plane.

Yet, six more stable axes may be found along lines drawn from the midpoint of the intersection of any two opposite faces to the midpoint of the intersection of the perpendicular opposite two faces. When the axes are set up in this manner, a duplication of the first three stable axes occurs. The moment of inertia of these six axes may be determined by applying the inclined axis transfer theorem (appendix I, equation 9; see also ref. 3), and may be shown to be equal to $I_{x'x'} = \frac{mS^2}{6}$ for this set of rotated axes. Other axes may be found having the same moment of inertia. A logical choice would be axes passing diagonally through two opposite corners. There is some stability about these axes, but it is to a lesser degree. Although a cube is symmetrical about these axes, it is not symmetrical about every axis passing through the center of mass (figures 15 and 16).

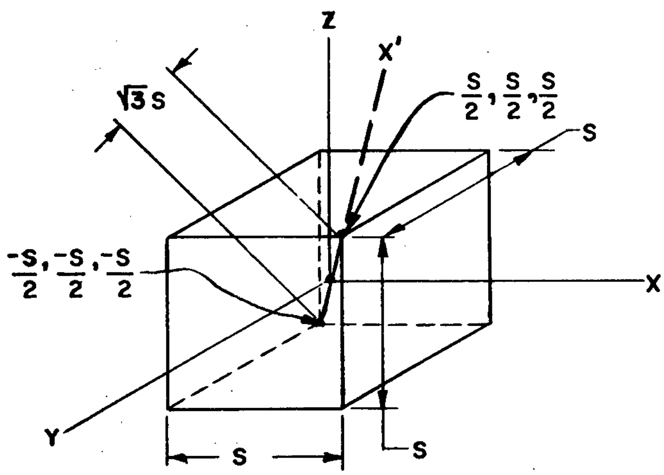


Figure 15. Rotated Axis Position No. 1 - Cubic

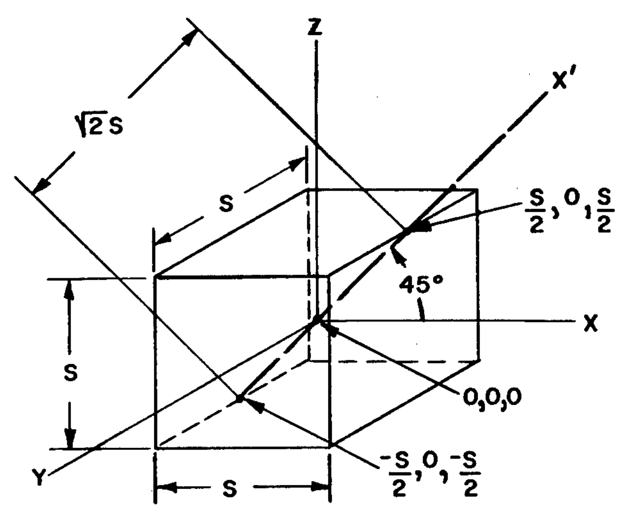


Figure 16. Rotated Axis Position No. 2 - Cubic

As the geometrical shape of the model approaches that of a sphere, the number of stable axes approaches infinity. This is true since the minimum moment of inertia of a sphere is equal to the maximum moment of inertia, and they both occur about each axis of the sphere, and each axis is an axis of symmetry.

Of primary importance in this discussion is man himself. The moment of inertia about the Z-axis (figure 5) of man is the minimum. Thus, man can expect rotation about the Z-axis to be stable. The maximum moment of inertia for man occurs about the X-axis, and therefore some stability may be achieved from rotation about X. For man, however, the moment of inertia about the Y-axis is very nearly equal to the moment of inertia about the X-axis (ref. 2). Thus, the stability characteristics about these two axes will be similar. Since they are so close in magnitude, the potential for stability about the X-axis will decrease somewhat and therefore stability about the Z-axis will be more pronounced. Hence man is seen to be most stable about the axis from head to foot through the center of mass. Since man is most stable about this axis, it can be said that if he was forced into a tumble and could maneuver himself close to the Z-axis, he could apply one of the Z-axis maneuvers which would resolve the rotation to one totally about Z. However, recovering from this rotation would be difficult.

QUANTITATIVE EVALUATION

In this section, a theoretical evaluation is made of the effectiveness of body-limb manipulation in producing rotation while weightless. A simple model was drafted to simulate the mass and moments of inertia of principal parts of the body, and then by calculation, to show the amount of rotation that can be achieved through purposeful limb manipulation.

Since the maneuvers discussed previously were not complex, the model was as simple as possible within the limits of realism. Cylinders were chosen as the shape of the segments, since their properties are well known. Six right circular cylinders were positioned to represent two arms, two legs, torso, and head, and they were so connected to allow all normal body movements.

Information concerning sizes and weights was given by the Anthropology Section of the 6570th Aerospace Medical Research Laboratories and taken from Dempster (ref. 2). The model man was constructed from 50th percentile data based on the 1950 survey of USAF personnel (ref. 6, also appendix I). Basic dimensions are shown in table I. From this data, the volume of each cylinder can be calculated and from the volume of each cylinder, its diameter can be calculated. The formula used is as follows:

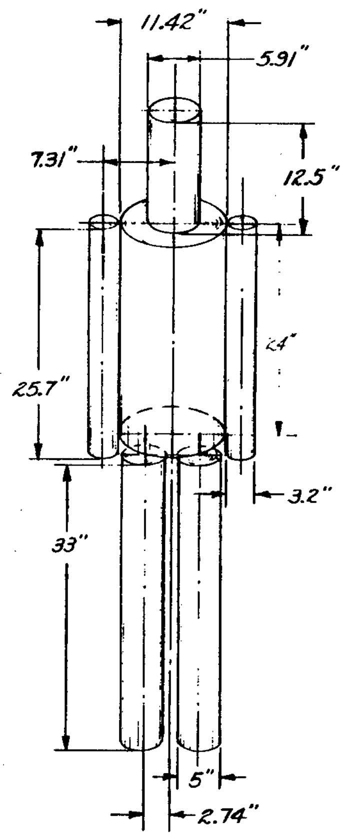
$$d = \sqrt{\frac{1.273\ V}{L}} \qquad \text{(see appendix I, equation 11)}$$

Individual measurements and a sketch of the model are shown in figure 17A and 17B. If the individual weights of the body segments are added together, the sum will not equal the total body weight, because the percent of total body weight is a mean for each segment in the survey, while the total body weight is a mean for each entire body in the survey. Thus, a discrepancy will exist due to the differences between individuals. Since the model man is an approximation, and the discrepancy is not great, the error may be accepted within the accuracy of this investigation.

TABLE I

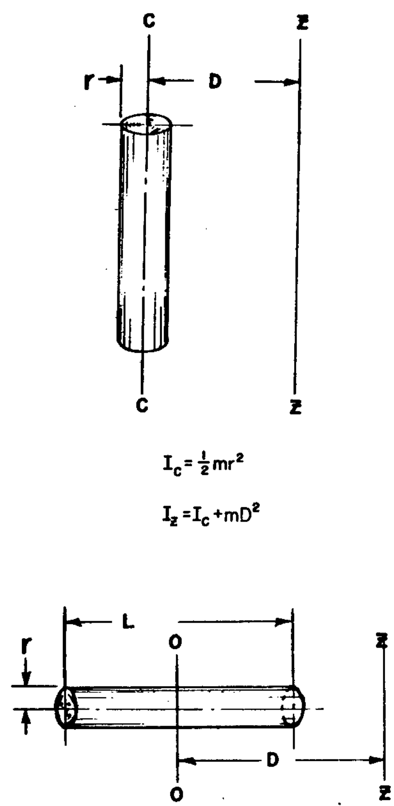
PROPERTIES OF MODEL MAN

SEGMENT	HEAD	TORSO	ARM	LEG
Percent of Total wt.	7.9	56.5	4.8	15.7
Weight (lb)	12.92	92.38	7.85	25.67
Mass (Slugs)	0.402	2.865	0.244	0.798
Length (ft)	1.042	2.000	2.040	2.750
Length^2 (ft^2)	1.085	4.000	4.160	7.560
Radius (ft)	0.246	0.475	0.133	0.208
Radius^2 (ft^2)	0.061	0.226	0.018	0.043
I_C (slug-ft^2)	0.012	0.324	0.002	0.017
I_O (slug-ft^2)	0.043	1.118	0.086	0.512



WEIGHT OF HEAD = 12.92 LB.
WEIGHT OF TORSO = 92.38 LB.
WEIGHT OF EACH ARM = 7.85 LB.
WEIGHT OF EACH LEG = 25.67 LB.
TOTAL BODY LENGTH = 69.5 IN.

Figure 17A. Model Man in Detail



$$I_C = \frac{1}{2} m r^2$$

$$I_Z = I_C + mD^2$$

$$I_O = \frac{1}{12} m (3r^2 + L^2)$$

$$I_Z = I_O + mD^2$$

Figure 17B. Axis Definitions of Moment of Inertia of Cylindrical Segments

Another reason for error is that the following calculations are based upon a rigid figure; and moments of inertia for various positions will differ from expected values based upon a flexible man. Hence, the resulting accuracy is not representative of an actual case. However, when the moments of inertia for a flexible man in various positions are determined, the equation for net angular displacement (appendix I, equation 6) will still hold.

Since the model man is now defined, we may begin to evaluate a movement. The movement to be evaluated is Z.1 the cat reflex maneuver. To repeat, this movement involves spreading the legs, twisting at the waist, closing the legs, spreading the arms, and returning to an untwisted attitude. The formula describing the net angular change of one cycle of the motion is derived in appendix I and is repeated here:

$$\Delta = \beta \left[\frac{I_{l_1}}{I_{l_1} + I_{u_1}} - \frac{I_{l_2}}{I_{l_2} + I_{u_2}} \right] \tag{6}$$

Assuming the total amount of the upper part of the body that can be twisted with respect to the lower part (β) is 90°, the only unknowns remaining are the moments of inertia. These are now calculated by using the equations for the moment of inertia of a right circular cylinder about a principal axis through the center of mass, and by applying the parallel-axis and inclined-axis transfer theorems (appendix I).

For condition 1, illustrated in figure 18 (arms down, legs spread), moments of inertia are taken about the Z-axis

$$I_{u_1} = 0.521 \text{ slug-ft}^2$$

Solving for I_l using the inclined axis transfer theorem:

$$I_{l_1} = 2(l'_{z'z})^2 I_{zz} + 2(l'_{z'x})^2 I_{xx} + 2(l'_{z'y})^2 I_{yy} + 2mD^2$$

The direction cosine $l'_{z'z}$ is the cosine of the angle that the rotated (Z') axis makes with the original (Z) axis. The direction cosine $l'_{z'x}$ is the cosine of the angle that the Z'-axis makes with the X-axis. The direction cosine $l'_{z'y}$ is the cosine of the angle that the Z-'axis makes with Y-axis.

$$l'_{z'z} = \cos 30° = \frac{\sqrt{3}}{2}$$

$$l'_{z'x} = \cos 90° = 0$$

$$l'_{z'y} = \cos 60° = \frac{1}{2}$$

$$I_{l_1} = 1.038 \text{ slug-ft}^2$$

For condition 2, illustrated in figure 18, (arms extended to the sides)

$$I_{u_2} = 1.600 \text{ slug-ft}^2$$

And since the legs return to their normal position

$$I_{l_2} = 0.117 \text{ slug-ft}^2$$

Now that the moments of inertia are known for each condition, we can proceed to determine the net angular displacement.

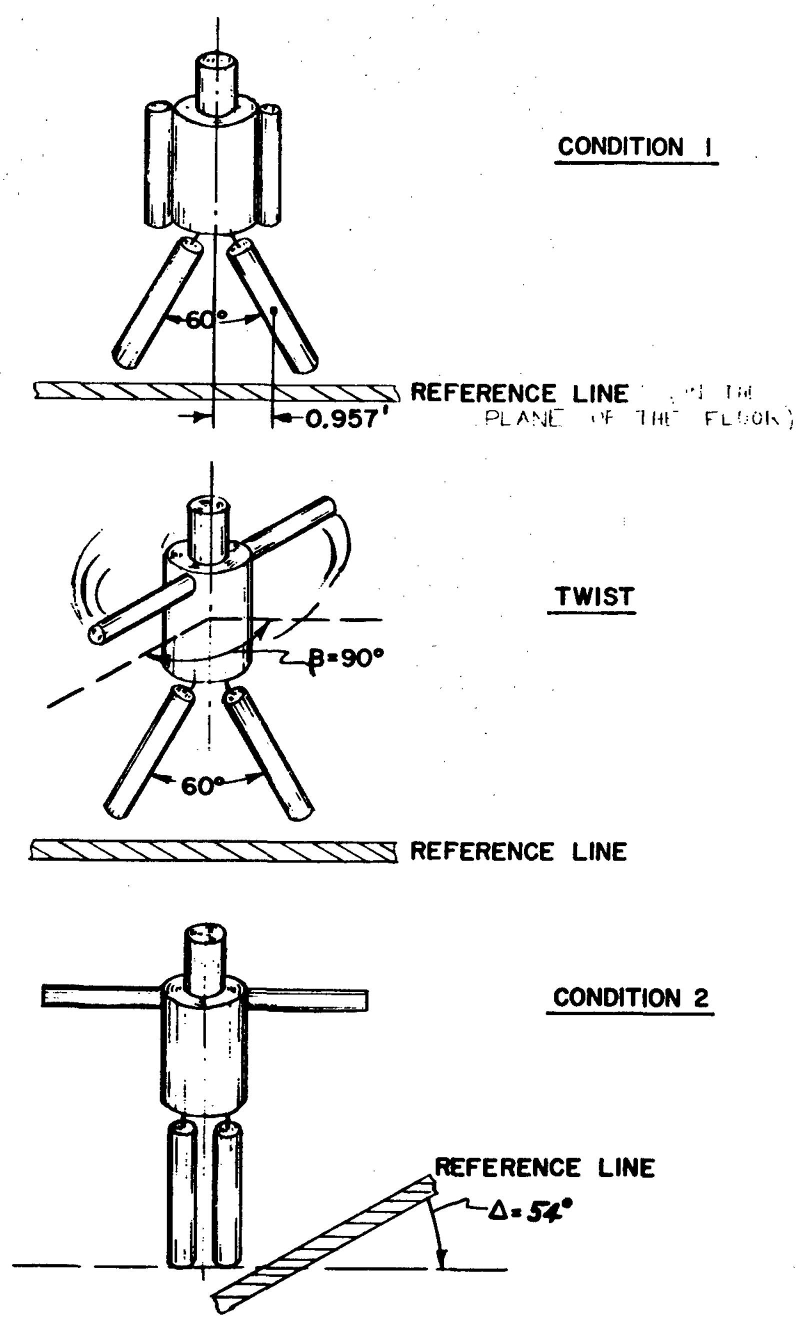


Figure 18. Axis Definitions of Moment of Inertia of Cylindrical Segments

$$\Delta = \beta\left[\frac{I_{l_1}}{I_{l_1} + I_{u_1}} - \frac{I_{l_2}}{I_{l_2} + I_{u_2}}\right] \quad \text{(appendix I, equation 6)}$$

and, assuming $\beta = 90°$ (angle of twist of upper portion relative to lower portion).

$$\Delta = 90°\left[\frac{1.038}{1.038 + 0.521} - \frac{0.117}{0.117 + 1.600}\right]$$

$$\Delta = 54°$$

Thus, after one cycle of twisting the upper part of the body 90 degrees and then untwisting to the original body position, the body as a whole will have rotated 54 degrees about the Z-axis. If the moment of inertia of the lower body were to approach infinity for condition 1, and if the moment of inertia of the upper body were to approach infinity for condition 2, the maximum angular displacement would equal 90 degrees, the initial angle of twist.

This example is presented to show the procedure for evaluating any physical movement. Thus, each of these or any similar movements can be categorized and listed as to their ease of operation and practical application. What remains to be done is the experimental determination of moments of inertia for man in various positions, and the analysis of each movement as to the resulting angular displacement and possible side effects due to assymetry. Finally, the movements should be validated experimentally to find a correlation between the mathematical analysis and the practical applicability. These experiments could be performed during zero-G flights.

In equation 6, the angle of twist (β) is an independent variable. Ninety degrees was chosen as the angle, since it is not only easily recognizable, but also seemed close to the maximum for a man. If the desired angular rotation is less than 54 degrees, all that is necessary is to reduce the angle of twist proportionately. If the desired angle of twist is greater than 54 degrees, more than one cycle of the maneuver could easily be performed.

The angle of spread of the legs and arms can also be regulated and will affect the total rotation. The easiest methods of performing the maneuver can only come from practice; and each individual may have a different performance technique that should approach the most efficient methods.

DISCUSSION

The nine self-rotation maneuvers in this report may provide a starting point for deriving and classifying the most efficient procedures for becoming rotationally self-sufficient in a frictionless environment. Since man can readily acclimate to new environments, the astronaut should become more at ease in space with each successive venture. Since a stable attitude of the body is necessary for virtually all operations in outer space, some form of self-rotation training will be a necessity for all astronauts. This training could be supplemented by actual classes in self-rotation aboard zero-G aircraft.

These nine maneuvers and any forthcoming maneuvers could readily be validated aboard such an aircraft. However, there will be problems in performing a validation of this type, such as the period of weightlessness, random accelerations of the aircraft, recording data, workspace limitations, and such factors as airsickness and random tumbling (ref. 4). The short period of weightlessness may be partially compensated for by the repetition of the weightlessness maneuver. Uneven accelerations of the aircraft may be tracked by an additional free-floating mass. Recording of data will certainly be aided by the installation of a telemetry system that will record and transmit accelerations directly from the free-floating subject within the aircraft. Workspace limitations may be partially alleviated with the use of a drop-table to suspend the subject in mid-air.

Problems associated with the development of an insulated and pressurized space suit that will allow freedom of movement will have to be overcome; other problems may be uncovered as the tests progress.

Inflight validation of these maneuvers will also be helpful in other areas. The motion of a tethered man will be more stable if he is able to react to undesirable rotations and control them. Knowledge of the maneuvers would improve both the man's confidence and performance. Although self-maneuvering units such as gas-expulsion stabilization belts and gyro-augmented stabilization units will be developed, there will always be a requirement for knowledge about self-rotation, if only as a provision against mechanical failure.

For a proper study of any self-rotation maneuver, the moments of inertia for flexible man must be determined. A computer study is planned in this area by Anthropology Section, Behavioral Sciences Laboratory. The experimental determination of moments of inertia for various body positions could easily be carried out using turntables mounted on spiral springs from which the period of oscillation could be measured and hence the moment of inertia could be easily calculated for each posture. Another method of measuring the period of oscillation is through the use of equipment based on the principle of the pendulum. Moments of inertia experimentally determined and compared with the computer study will be a time-saving aid to the analysis of any self-rotation maneuver.

The model man was constructed of six cylinders placed in such a manner that the shape and mass of man may be reasonably approximated. It is, however, only an approximation. Therefore, values calculated for the angular displacement in each maneuver, when compared to the true displacement for a man, are only approximate. Yet, since the model is based on measurements of human subjects, the order of magnitude of moments of inertia for the model will be comparable to that for a man. When moment of inertia data for flexible man is taken, a more sophisticated model, one that better approximates a human being, may be developed. When this is accomplished, a technique may be developed to rapidly evaluate any self-rotation movement. Numerous variations of each maneuver described are possible. An evaluation of each variation would be desirable to classify and optimize them and, in the process, perhaps discover new motions.

In keeping with this classification, we may state 10 general rules governing the art of self-rotation:

1. Any self-rotation maneuver must contain a change of limb or torso attitude accompanied by a corresponding change of moment of inertia.

2. The change of limb or torso attitude must result from some form of twisting or continuous rotary motion of the limbs or torso.

3. The change of moment of inertia must result from the extension of limbs, or the extension of masses from the limbs.

4. The twisting motion must contain a four part cycle: an initial state, a twist about the axis of intended rotation, a change of moment of inertia, and a return to the initial state.

5. Any form of twisting or continuous rotary motion consists of a single cycle of inertia change of one part of the body with respect to the remainder of the body.

6. In general, assymmetric rotations are difficult to perform, create side effects, are unstable, and undesirable.

7. In general, symmetric rotations are easy to perform, free from side effects, stable, and desirable.

8. Rotations about stable axes are stable rotations.

9. The most rotationally stable axis for man is the axis that passes from head to foot and through the center of mass of the body.

10. Although testing any self-rotation maneuver is more readily performed on a frictionless platform than in a zero-G aircraft, the process is less efficient, because of a center of mass misalignment from the axis of rotation, and a lack of coupling (due to restrictions on the freedom of the subject).

In summary, a man in a weightless environment with no external forces, can, by means of body-limb manipulation, change his body orientation by rotation. At no time, however, does the center of mass of the body as a whole move through space. The man may change the relative angular momentum of various portions of his body through limb manipulation, but the total angular momentum is constant. For example, if the body had some initial angular velocity, he could rotate his arms and thus change the angular velocity of his body. When he stopped rotating his arms, however, the entire body would assume the initial angular velocity.

Any body maneuver may be analyzed by the laws of mechanics. And, following the laws of mechanics, the nine self-rotation maneuvers should be validated, expanded, and classified for the use of all space personnel.

Since the state of zero gravity is so prominent in space travel, and since these self-rotation techniques have been developed for use during space travel, proficiency in self-rotation may conceivably serve as a criterion for crew selection. Today's astronauts experience zero gravity for prolonged periods. While it is true that the astronauts have been strapped to their seats to restrict their motion in the workspace area, eventually they will have freedom of motion throughout the space vehicle, and unless they have some form of artificial gravity or adhesive devices on their feet to keep their position fixed, they will have to know self-rotation well enough to do their work. Material handling under zero gravity is another area that could serve as a criterion for crew selection, for there must be safeguards against mechanical failure even if it means making repairs by hand. Knowledge of self-rotation is also required in this area.

Another related area is that of self-locomotion. Man cannot translate when placed in a weightless condition; but if he has a surface from which he can push, he can translate to a new position in space. This type of motion is called soaring and the path traveled is called a trajectory. Proficiency in self-locomotion may also be a criterion for crew selection, for the ability to self-locomote should be a requirement, if only as a safety factor.

These three criteria: self-rotation, material handling, and self-locomotion can all be tested aboard zero-G aircraft and in fact may become a necessary part of an astronaut's training .

These self-rotation maneuvers have been designed so they are best performed when maximum freedom of movement is available. Yet, it is true that in a space environment an insulated and pressurized space suit is absolutely essential. The suits already in existence, however, limit flexibility so much that an individual cannot bend over while wearing one. Two solutions to this problem are immediately obvious. Either the suits must be modified to allow normal flexibility, or the movements must be modified to be effective with limited mobility. We cannot expect the first of these solutions to be available in the near future although it must continue to be a goal. Therefore, we are left with only one choice, that is, to modify the movements to give maximum rotation with present limitations on mobility. The movements dealing primarily with arm rotations should prove to be the easiest to perform, although the efficiency of the rotation will be greatly decreased. Movements dealing with bending at the waist would probably be energy consuming and inefficient. Finally, movements having a 4-stage cycle would not be desirable, since they have more motions than do continuous rotary maneuvers, thus are more difficult to perform. However, the maneuvers, classified according to their ease of application with limitations on maneuverability, should be an integral part of the inflight validation.

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APPENDIX I

DERIVATION OF FORMULAS

LIST OF SYMBOLS

t = time (sec)

m = mass (slugs)

F = force (lb)

L = length of cylinder (ft)

S = length of side of cube (ft)

D = perpendicular distance from reference axis to axis of rotation (ft)

r = radius to outer fiber (ft)

a = linear acceleration (ft/sec^2)

θ = angular displacement (radians)

ω = angular velocity (radians/sec)

α = angular acceleration (radians/sec^2)

β = angle of twist (radians or degrees)

Δ = angular displacement after maneuver (radians or degrees)

T = torque (lb-ft)

P = linear momentum (slug-ft/sec)

H = angular momentum (lb-ft-sec)

I = moment of inertia (lb-ft-sec^2)

l' = direction cosine

V = volume (cu. ft)

ρ = mass density (slugs/cu. ft)

SUBSCRIPTS

u = upper portion of body (includes torso, arms, head)

l = lower portion of body (legs)

H = head

A = arm

T = torso

L = leg

C = about centroidal axis

O = about transverse axis

Z = about Z-axis

Y = about Y-axis

X = about X-axis

Z' = about rotated Z-axis

Y' = about rotated X-axis

N = any axis

1 = initial state

2 = changed state

BASIC EQUATIONS USED

(a) $F = ma$

$T = I\alpha$

(b) $H = I\omega$

(c) $\omega = \frac{d\theta}{dt}$

$\alpha = \frac{d^2\theta}{dt^2}$

(d) $I_c = \frac{1}{2} mr^2$ (for a right circular cylinder about its axis of symmetry)

(e) $I_o = 1/12m\ (3r^2 + L^2)$ (for a right circular cylinder about its transverse axis)

(f) $I_n = I_c + mD^2$ (parallel-axis theorem)

DERIVATION OF EQUATIONS

a. A torque on the upper body is reacted to by a torque on the lower body

1. $T_u = I_u \alpha_u \qquad T_l = I_l \alpha_l$

2. $\alpha = \dfrac{d^2\theta}{dt^2}$

3. $T = I \dfrac{d^2\theta}{dt^2}$

4. $I_u \theta_u = \iint T \, dt \, dt$ where I_u and I_l

$I_l \theta_l = -\iint T \, dt \, dt$ remain constant

5. $I_u \theta_u = -I_l \theta_l$

6. $\dfrac{\theta_u}{\theta_l} = -\dfrac{I_l}{I_u}$ (Equation 1)

Equation 1 may also be derived from the rotational analog of the conservation of momentum. This equation will not hold if the moments of inertia change as the angular displacements change according to some function of time. If the moments of inertia are not a function of time, as in the cat reflex maneuver, the equation is correct.

b. If a man performed some movement, then changed his moment of inertia, and performed the same movement in reverse, the result would be a net displacement of the man.

1. $\dfrac{\theta_{u_1}}{\theta_{l_1}} = -\dfrac{I_{l_1}}{I_{u_1}}$

$\dfrac{\theta_{u_2}}{\theta_{l_2}} = -\dfrac{I_{l_2}}{I_{u_2}}$ (Equation 2)

2. The angle β is defined to be

$\beta = \theta_{u_1} - \theta_{l_1} = \theta_{u_2} - \theta_{l_2}$ (Equation 3)

3. From equation 1 and 2

$\theta_{l_1} = -\dfrac{I_{u_1}}{I_{l_1}} \theta_{u_1}$

$\theta_{l_2} = -\dfrac{I_{u_2}}{I_{l_2}} \theta_{u_2}$

4. Substituting into equation 3,

$$\theta_{u_1} + \frac{I_{u_1}}{I_{l_1}} \theta_{u_1} = \theta_{u_2} + \frac{I_{u_2}}{I_{l_2}} \theta_{u_2}$$

$$\theta_{u_1} \left[1 + \frac{I_{u_1}}{I_{l_1}} \right] = \theta_{u_2} \left[1 + \frac{I_{u_2}}{I_{l_2}} \right]$$

5. Multiplying by I_{l_1} I_{l_2},

$$\theta_{u_1} I_{l_2} (I_{l_1} + I_{u_1}) = \theta_{u_2} I_{l_1} (I_{l_2} + I_{u_2})$$

6. The net change of attitude is

$$\Delta = \theta_{u_1} - \theta_{u_2} = \theta_{l_1} - \theta_{l_2}$$

7. Solving for θ_{u_2} from step 5, and substituting,

$$\Delta = \theta_{u_1} - \theta_{u_1} \left[\frac{I_{l_2}}{I_{l_1}} \right] \left[\frac{I_{l_1} + I_{u_1}}{I_{l_2} + I_{u_2}} \right] \qquad \text{(Equation 4)}$$

8. Substituting equation 3 in equation 1, and rearranging,

$$\theta_{u_1} = \beta \left[\frac{I_{l_1}}{I_{l_1} + I_{u_1}} \right] \qquad \text{(Equation 5)}$$

9. Substituting equation 5 into equation 4, gives

$$\Delta = \beta \left[\frac{I_{l_1}}{I_{l_1} + I_{u_1}} - \frac{I_{l_2}}{I_{l_2} + I_{u_2}} \right] \qquad \text{(Equation 6)}$$

c. Finding the moment of inertia of a rectangular parallelepiped about its principal axes (figure 14).

1. $I = \int r^2 \, dm$

2. Suppose the sides whose lengths are a, b, and c are parallel to the x, y, and z axes, respectively; and the moment of inertia about the Z-axis is desired.

3. The term r^2 then is changed to $x^2 + y^2$ in rectangular coordinates. The mass dm can be written as the product of the mass density (ρ) times the differential volume (dV)

$$r^2 = x^2 + y^2$$

$$dm = \rho \, dV = \rho \, dx \, dy \, dz$$

4. $$I_{zz} = \rho \int_{z=-\frac{c}{2}}^{\frac{c}{2}} \int_{y=-\frac{b}{2}}^{\frac{b}{2}} \int_{x=-\frac{a}{2}}^{\frac{a}{2}} (x^2 + y^2)\, dx\, dy\, dz$$

(assuming that ρ remains constant)

5. $$I_{zz} = \rho \int\int\int x^2\, dx\, dy\, dz + \rho \int\int\int y^2\, dx\, dy\, dz$$

6. $$I_{zz} = \rho \int\int \frac{a^3}{12}\, dy\, dz + \rho \int\int a\, y^2\, dy\, dz$$

7. $$I_{zz} = \rho \int \frac{a^3}{12}\, b\, dz + \rho \int a\, \frac{b^3}{12}\, dz$$

8. $$I_{zz} = \rho \frac{a^3 b c}{12} + \rho \frac{a b^3 c}{12}$$

9. $$I_{zz} = \rho\, a b c \left[\frac{a^2 + b^2}{12}\right]$$

10. But $\rho\, abc = m$

11. $$I_{zz} = m\frac{(a^2 + b^2)}{12} \qquad \text{(Equation 7)}$$

12. In the same manner, it may be shown that

$$I_{yy} = \frac{m(a^2 + c^2)}{12}, \text{ where } r^2 = z^2 + x^2$$

$$I_{xx} = \frac{m(b^2 + c^2)}{12}, \text{ where } r^2 = y^2 + z^2$$

13. For a cube, $a = b = c = S$

$$I_{xx} = I_{yy} = I_{zz} = \frac{m(S^2 + S^2)}{12}$$

$$I_{cube} = \frac{mS^2}{6} \qquad \text{(Equation 8)}$$

This may also be proved by a similar integration as shown above.

d. Inclined axis transfer theorem, applied to finding the moment of inertia of a cube about an axis rotated 45° from a principal axis:

1. If X' is rotated 45° from the X-axis, in the XZ plane, the direction cosines for a cube are

$$l'_{xx'} = \frac{S}{\sqrt{2S^2}} \quad \frac{\sqrt{2}}{2}$$

$$l'_{yx'} = \frac{\sqrt{2}}{2}$$

$$l'_{zx'} = 0, \text{ and}$$

$$I_{zz} = I_{yy} = I_{xx} = \frac{mS^2}{6}$$

2. The inclined axis theorem states (ref. 3):

$$I_{x'x'} = (l'_{x'x})^2 I_{xx} + (l'_{x'y})^2 I_{yy} + (l'_{x'z})^2 I_{zz} \quad \text{(Equation 9)}$$

3. Therefore, for a cube with the axes rotated 45° in one plane

$$I_{x'x'} = \left[\frac{\sqrt{2}}{2}\right]^2 \frac{mS^2}{6} + \left[\frac{\sqrt{2}}{2}\right]^2 \frac{mS^2}{6} + 0$$

$$I_{x'x'} = \frac{mS^2}{6}$$

4. If the principal axes were rotated such that each axis was a diagonal of the cube, all the direction cosines would be

$$l' = \frac{S}{\sqrt{3S^2}} = \frac{\sqrt{3}}{3} \qquad \text{(see figure 16)}$$

and the moment of inertia about each of these axes would be

$$I = \left[\frac{\sqrt{3}}{3}\right]^2 \frac{mS^2}{6} + \left[\frac{\sqrt{3}}{3}\right]^2 \frac{mS^2}{6} + \left[\frac{\sqrt{3}}{3}\right]^2 \frac{mS^2}{6}$$

$$I = \frac{mS^2}{6}\left[\frac{3}{9} + \frac{3}{9} + \frac{3}{9}\right]$$

$$I = \frac{mS^2}{6} \quad \text{(Equation 10)}$$

which is as expected since the moment of inertia about each principal axis is constant. and since we know from analytic geometry that the sum of the squares of the direction cosines is equal to 1. This moment of inertia may be shown to be the maximum for a cube.

e. Diameter of each cylinder is calculated as follows:

1. The specific weight of the model is equal to the specific gravity of the model multiplied by the specific weight of water.

$$W = (1.04)\,(62.5) = 65 \text{ lb/cu.ft}$$

2. The volume of a particular part is equal to the weight of that part, divided by the specific weight

$$V = \frac{\text{SEGMENT WEIGHT}}{W}$$

3. The volume of a particular part is also equal to the area of the base times the length of the cylinder

$$V = \frac{\pi d^2 L}{4}$$

4. Solving for the diameter, d

$$d = \sqrt{\frac{4V}{\pi L}} = \sqrt{\frac{1.273\,V}{L}} \qquad \text{(Equation 11)}$$

DETERMINATION OF THE MODEL MAN

All data for the construction of the model is as follows. From Dempster (ref. 2, p. 27) the leg length is equal to the crotch height of the median study sample. The arm length is the sum of the shoulder-elbow length and the forearm-hand length of the median study sample (ref. 2, p. 30). The torso length is the difference between acromion height standing and the crotch height of the median study sample (ref. 2, p. 27). The head length is the difference between total stature and acromion height of the median study sample.

The following weight distribution is contained in Dempster (ref. 2, pp. 186-188) and is based upon the mean of eight cadavers. The head is 7.9 percent of total body weight. The torso is 56.5 percent of total body weight. Each leg is 15.7 percent of total body weight. Similarly, each arm is 4.8 percent of total body weight.

The total body weight is 163.5 lb., the mean for all subjects in the 1950 USAF survey (ref. 5). Similarly, the total body height is 5 ft., 9 1/2 inches; and from Dempster (ref. 2, p. 195), specific gravity is 1.04 as calculated from mass data on cadaver parts and volume data derived by immersion in water.

If the total body weight and each segment's percent of total body weight are both known, then by multiplying the two, each segment's weight is known. Since specific gravity is a ratio of specific weight to the specific weight of water, the specific weight of the model can be determined readily.

The volume of any segment is determined from the above data by dividing the weight of that segment by its specific weight. This volume is then equated to the mathematical expression for the volume of a cylinder, $V = \frac{\pi d^2 L}{4}$, and since the diameter (d) is the sole unknown, it is readily calculated.

In spacing the segments, symmetry was stressed. The head was placed on the torso such that their axes of symmetry coincide. The arms were placed at equal distances from this axis and are flush along the torso. The legs were placed such that there was as much separation between legs as there was between the outer surface of the leg and the outer surface of the torso. Relevant dimensions and weights are located in figure 17.

APPENDIX II

THE EFFECT OF ADDITIONAL MASS ON SELF-ROTATION

It has been shown that the effectiveness with which one can self-rotate depends primarily upon body-limb positioning to give a select moment of inertia ratio. One would expect that by attaching external masses to the limbs, this moment of inertia ratio can be increased for each position and therefore the ease and amount of rotation can be increased for each maneuver. In this section, the degree of rotation is examined for the "cat reflex" maneuver after a mass (m) has been added to the legs or arms of the model man. For simplicity, the masses are chosen to have an identical shape, and an identical but unknown mass (m). The mass is represented by a letter, in order that the effects on rotation may easily be determined for a range of masses. The shape of the mass is spherical, the radius being six inches. The moment of inertia through its center of mass is then

$$I_S = \frac{2}{5} mr^2 = \frac{2}{5} m(0.5)^2 = \frac{m}{10} \text{ slug-ft}^2$$

For condition 1 (arms down, legs spread), moments of inertia are taken about the Z-axis.

$$I_{u_1} = 0.521 + 2I_S + 2mD^2$$

$$I_{u_1} = 0.521 + 0.942\,m \text{ slug-ft}^2$$

and solving for I_{l_1}

$$I_{l_1} = 1.038 + 2I_S + 2mD^2$$

$$I_{l_1} = 1.038 + 6.922\,m \text{ slug-ft}^2$$

For condition 2 (arms extended, legs in)

$$I_{u_2} = 1.600 + 2I_S + 2mD^2$$

$$I_{u_2} = 1.600 + 19.402\,m \text{ slug-ft}^2$$

and, solving for I_{l_2}

$$I_{l_2} = 0.117 + 2I_S + 2mD^2$$

$$I_{l_2} = 0.117 + 0.304\,m \text{ slug-ft}^2$$

Using these moments of inertia, we now find the angular displacement for any mass having the same spherical shape that may be added for this same maneuver.

$$\Delta = \beta \left[\frac{I_{l_1}}{I_{l_1} + I_{u_1}} - \frac{I_{l_2}}{I_{l_2} + I_{u_2}} \right] \qquad \text{(Equation 6)}$$

Once again assuming $\beta = 90°$

$$\Delta = 90° \left[\frac{1.038 + 6.922\,m}{1.559 + 7.864\,m} - \frac{0.117 + 0.304\,m}{1.717 + 19.710\,m} \right]$$

It is recalled that for a mass of zero slugs, Δ = 54°
and, for a mass of 0.1 slug, Δ = 62.7°,
for a mass of 0.2 slug, Δ = 66.8°,
for a mass of 0.3 slug, Δ = 69.1°,
for a mass of 0.5 slug, Δ = 71.5°, and
for a mass of 1.0 slug, Δ = 74.4°

It is interesting to note that the addition of a one slug mass (weighing 32.2 lb. at one g) to each limb will only increase the angle of rotation 20.4 degrees. Two consecutive cycles of the same maneuver without masses would probably be easier to perform than a single cycle with masses. As masses are added, the force necessary to impart momentum to the limbs increases; and with large masses such as one slug this force would be appreciable. Therefore, the addition of mass would be impractical, unless the mass was "useful mass," and it would not effectively enhance rotation for this maneuver.

It remains to be seen, however, whether adding masses would be desirable for other maneuvers. It seems likely that maneuvers involving continuous rotations of the arms or legs would be advanced by the addition of masses. While it is true that this condition would demand extra force to begin the motion, rotation of the arms or legs would be easier to maintain, since the greater momentum of the limb tends to keep the arm rotating much in the manner of the flywheel of an automobile. It is also true that extra force would be required to stop the motion. Experimental validation should reveal whether the ease of rotation during the middle of each maneuver gives an advantage over the extra force required at the beginning and end of each maneuver.

For motions having a four component cycle, the addition of mass to the limbs would probably be undesirable, since the motion is oscillatory rather than rotary, and therefore more stops and starts are required.

Although a physical analysis could be made for each maneuver, the inflight validation with added masses would be a better approach for three reasons. First, a physical analysis would be only as accurate as the model that it is based upon. Second, such an analysis would be based upon the laws of rigid body dynamics, but a rotating human subject does not even approach the case of a rigid body. Third, the results of such an analysis would not merit the complexities such as variable moment of inertia, locations of the limbs in space, the velocity of rotating segment, the net angle of rotation, side effects due to coupling about axes other than the axis of rotation, effect of mass shapes and sizes on the limbs or on combinations of the limbs, time of rotation, etc. An inflight validation of each maneuver will provide data on many of these variables which could possibly be shown in the form of charts that may eventually be used to readily analyze the motion under select conditions.

It should be noted that in both the quantitative evaluation and in the evaluation with added masses, calculations were made with the legs separated by sixty degrees and the arms perpendicular to the torso. However, any angle of separation of the arms or legs in the proper sequence will lead to a rotation. Even if the legs are not split in either condition, the model man can rotate nearly 10.5 degrees of the rest of the maneuver is performed as previously stated. In this case, the addition of one slug masses to the arms decreases the angle of rotation to only 6.2 degrees; but if one slug masses are also added to the legs, the angle of rotation increases to 18.8 degrees; and if the masses are taken off of the arms, the angle of rotation would increase to 21.4 degrees. Since these are only some of the quantities that may be varied for this maneuver alone, the need for optimization of each maneuver should be clear.

The inflight validation should also show how accurate our model man is. Once an accurate model of flexible man is constructed, the theoretical aspects of the study may be furthered. In the meantime, the best way of studying these maneuvers is to consider the effects of each variable in an actual zero gravity condition. The calculations presented in this report may be classified only as general results, and whether or not additional mass will desirably affect body rotation could also be a part of inflight validation.

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6570th Aerospace Medical Research Laboratories, Wright-Patterson AFB, Ohio
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Final report, Oct. 62, iv + 40 pp. incl. illus., 10 refs. Unclassified report

To be an effective weightless worker, an individual must be able to achieve and maintain a stable attitude with respect to his vehicle. If the worker is to have this capability, he must be able to control both translation and rotation. Translation may not be controlled without hardware, whereas rotation may. The purpose of this study was to investigate the

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